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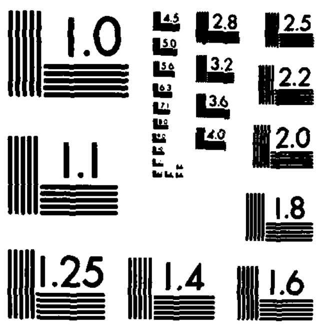
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REPORT 84-17

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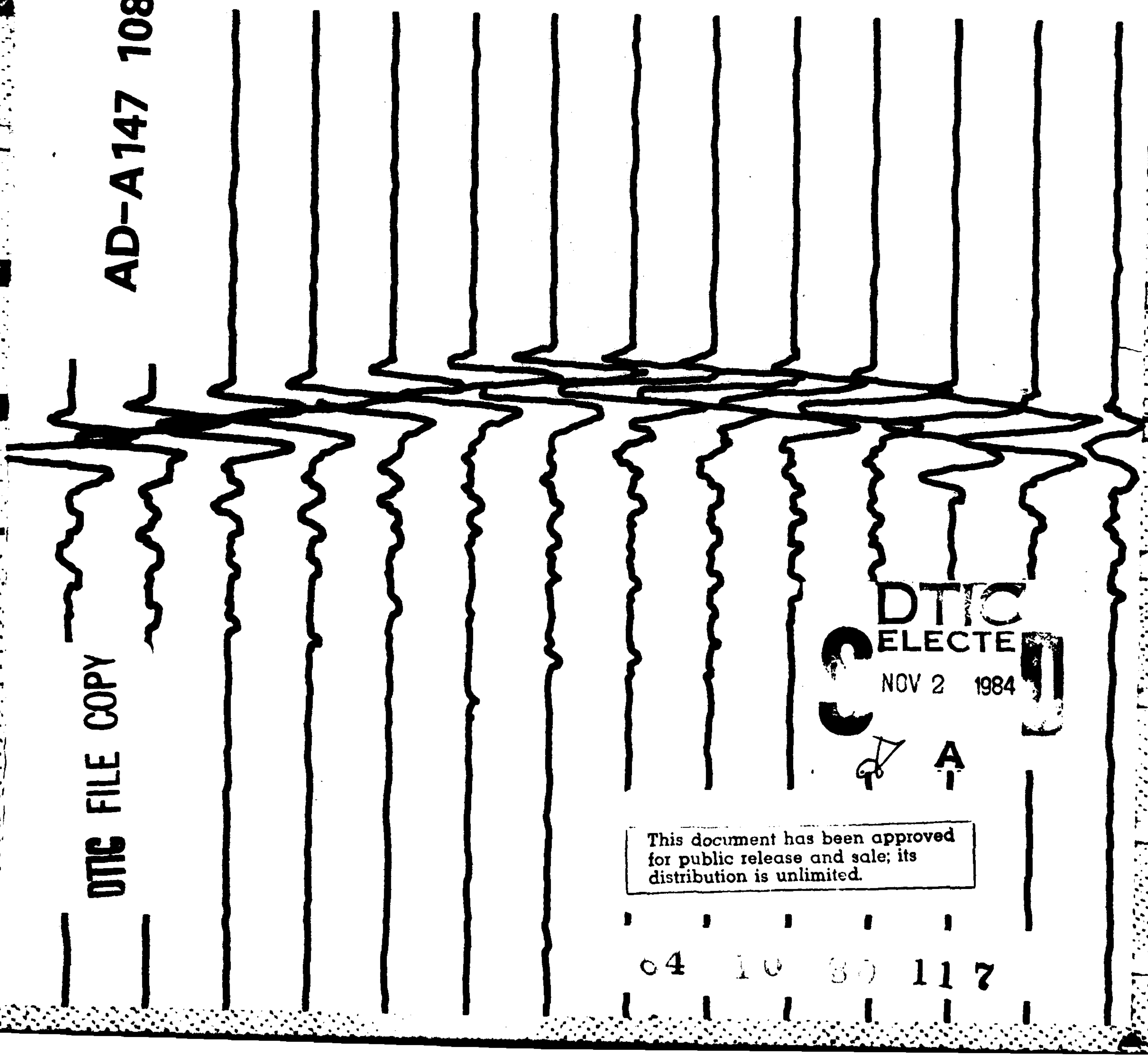
US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Pulse transmission through frozen silt



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Radar pulses transmitted through the frozen silt above the permafrost tunnel at Fox, Alaska.

CRREL Report 84-17

July 1984

Pulse transmission through frozen silt

Steven A. Arcone

Prepared for
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VHF-band radiowave short pulses were transmitted within the permafrost tunnel at Fox, Alaska, over distances between 2.2 and 10.5 m. The propagation medium was a frozen silt containing both disseminated and massive ice with temperatures varying from -7°C near the transmitter to probably -2°C near the center of the tunnel overburden. The short pulses underwent practically no dispersion in the coldest zones but did disperse and refract through the warmer overburden, as suggested by calculations of the effective dielectric constant. Most significantly the measured frequency content decreased as the effective dielectric constant increased. The results indicate that deep, cross-borehole pulse transmissions over distances greater than 10 m might be possible, especially when the ground is no warmer than -4°C. The information thus gained could be used for identifying major subsurface variations, including ground ice features.

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PREFACE

This report was prepared by Dr. Steven A. Arcone, Research Geophysicist, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by DA Project 4A161102AT24, *Research in Snow, Ice and Frozen Ground; Task C; Work Unit 005, Dielectric Characteristics of Frozen Soil.* This report was technically reviewed by Dr. Kenneth Jezek and Paul Sellmann of CRREL.

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PULSE TRANSMISSION THROUGH FROZEN SILT

Steven A. Arcone

INTRODUCTION

An important objective of geophysical exploration in permafrost regions is the delineation of subsurface ground ice. In interior and northern Alaska, fine-grain soils cover thousands of square miles to depths of up to 60 m. These soils contain large volumes of ice, and massive ice features such as wedges and lenses are common. This report discusses field observations of the propagation of electromagnetic pulses in the VHF band through this material. The purpose of this study was to see if one-way subsurface pulse transmissions could be useful for identifying subsurface conditions such as temperature or ice content.

Geophysical investigations of permafrost features within the upper 50 m of the earth have mainly used electromagnetic techniques. Seismic methods (Roethlisberger 1972) operate at wavelengths far too large to offer adequate resolution for ground ice features, whose largest dimensions seldom exceed several meters. Most shallow-penetrating electric and electromagnetic methods used for frozen ground studies have been surface based. Arcone et al. (1978, 1979) and Hoekstra (1978) have used magnetic induction methods to indicate zones of frozen material or massive ice. Bertram et al. (1972), Annan and Davis (1976), Davis et al. (1976), Kovacs and Morey (1979), Arcone et al. (1982) and Sellmann et al. (1983) have all reported on the use of ground-penetrating radar to detect massive ground ice. Although radar offers far more detail than magnetic induction and presents the possibility of deriving dielectric properties from the data, reflections are often limited to the shallowest reflector. In addition, multiple reflections, the multitude of diffractions, and the length of the basic pulse waveform can sufficiently complicate a record so that interpretation of significant details becomes difficult.

One of the primary attractions of radar has been its relative simplicity (compared with seismic profiling). Only two small antennas need be towed over the ground, and the control and recording units can be easily stowed on a vehicle or even carried by hand. This time-saving simplicity is helpful if the objective is to three-dimensionally delineate ground ice features, which would require several parallel survey lines. Unfortunately the antenna beamwidth is very wide over the bandwidths used, so reflections do not necessarily emanate from beneath the antennas. Alternatively one can utilize point-to-point transmission measurements of pulses propagated transversely (as between bore-

holes) or employ techniques similar to the seismic methods of refraction shooting and vertical profiling. The transmission studies presented here were preliminary to vertical-borehole profiling studies.

The objective of these studies was to determine how short VHF pulses are affected by transmission over distances on the order of 10 m through ice-rich frozen silt. Of particular interest was the degradation of pulse waveform, changes in amplitude, and time delay. The dielectric properties of ice-rich frozen silt have been documented by Hoekstra and Delaney (1974) and Delaney and Arcone (1982, 1984). Their data suggest that permafrost temperatures must be below about −2.0°C to ensure that radiowave energy losses associated with material conductivity or dipolar relaxation are sufficiently low to allow propagation over this distance.

PROCEDURES

Electromagnetic equipment

These tests were done with a commercially available radar profiling system with separable antennas. The separability allows one to monitor direct transmissions, as reported here, or indirect reflections, as is more commonly done in radar profiling. The separability also allows a choice in polarization.

The system emits pulses of several nanoseconds duration at a repetition rate of 50 kHz. The pulses are radiated and received with a broad-band, resistively loaded, bowtie-type dipole antenna. The pulse spectrum is centered at about 300 MHz when transmitting in air. The antennas become loaded when placed on the ground, which decreases the center frequency of the pulse spectrum to between 150 and 200 MHz and places the 3-db bandwidth generally between 80 and 300 MHz.

Echos, or arrival events, are reproduced in the audio range for display purposes by sampling techniques. The waveforms of individual events may be recorded digitally utilizing as many as 64 stacked scans to help eliminate incoherent noise. One of several gain functions that monotonically increase signal amplitude with time over a specified interval is usually applied to the events to compensate for the loss of amplitude with time of return.

Permafrost tunnel

The CRREL permafrost tunnel at Fox, Alaska, approximately 16 km north of Fairbanks, was chosen for these investigations because of the thick (8-10 m) silt overburden above the tunnel. The tunnel is an excavation into a nearly vertical escarpment of perennially frozen organic silts of Pleistocene age (Fig. 1). The upper drift of the tunnel is horizontal, about 122 m long, and it has a vertical shaft for ventilation. A lower drift begins about 37 m from the main entrance and descends at a slight grade for about 60 m until it ends in the underlying gravel and bedrock. Transmitting and receiving antennas were placed on either side of the overburden and on opposite walls of the septum dividing the drifts.

Ground ice incorporated in the sediment occurs as segregated small lenses and masses with dimensions on the order of millimeters, as large foliated wedges up to a few meters in width or depth, and as clear masses that may be tens of meters in one or more dimensions. Ice volumes of samples containing mineral material range from 54 to 79%

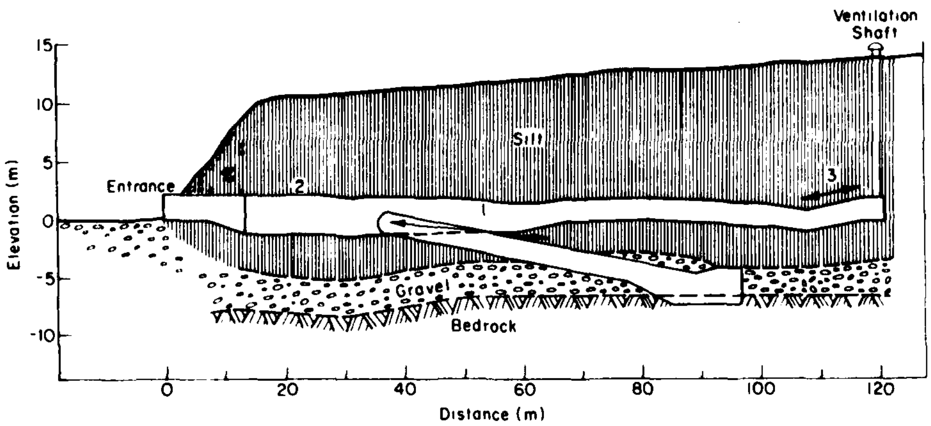


Figure 1. Sketch of tunnel cross section. The arrows indicate the areas of investigation.

(Sellmann 1967). The ice at the surface of the walls and ceilings has sublimated, leaving a porous layer of dry silt between 5 and 10 cm thick. The tunnel air temperature at the time of these studies (April 1982 and 1983) was −1.5 °C. However, since the tunnel is refrigerated in winter by circulating outside air, temperatures within the tunnel walls were considerably lower. Measurements within the septum dividing the two drifts revealed temperatures of approximately −7 °C between 1 and 2 m in depth.

RESULTS

Transmissions through the tunnel septum

This experiment was described previously (Arcone and Delaney 1984) and is reviewed here because of its relevance to this discussion of waveform degradation. A plan view of the septum separating the two tunnel drifts is shown in Figure 2 (area 1 on Fig. 1) with the pulses shown in Figure 3. The waveforms are clipped because the gain could not be monitored while the observations were performed. Each trace is a 64-fold stack. The electric field was horizontally polarized, with the receiving antenna slightly off broadside by the projected apex angle of the septum (about 20°).

The pulse frequency spectrum was consistently centered at about 180 MHz. The lack of variation in pulse shape indicates that no dispersion occurred as the propagation distance increased from 2.2 to 7.7 m. Three dielectric constant (x') values were computed for the time-distance slopes from the leading edges of the waveforms. A value of 3.9 was computed for stations 13–16, where there is a large ice wedge (Fig. 2). The x' value of pure ice is approximately 3.2, suggesting that only a small portion of the propagation paths at these stations was through ice-rich silt. The other slopes give x' values of 7.0 (stations 6–12) and 7.3 (stations 17–21), which agree with laboratory values (Delaney and Arcone 1982, 1984) for ice-rich silt (55% water by volume) at temperatures below −5 °C. Spot temperature measurements gave values between −4° and −8 °C (Fig. 2).

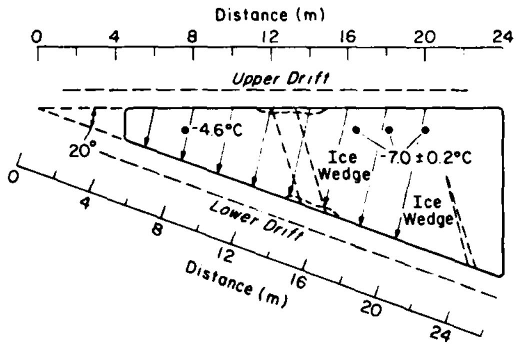


Figure 2. Plan view of the wedge-like tunnel septum across which pulses were propagated. Arrows indicate the placement of the transmitter (in the upper drift) and the receiver (in the lower drift). Numbers within the septum refer to spot temperature measurements, taken between 1 and 2 m deep. Dashed zones suggest likely limits of ice wedges.

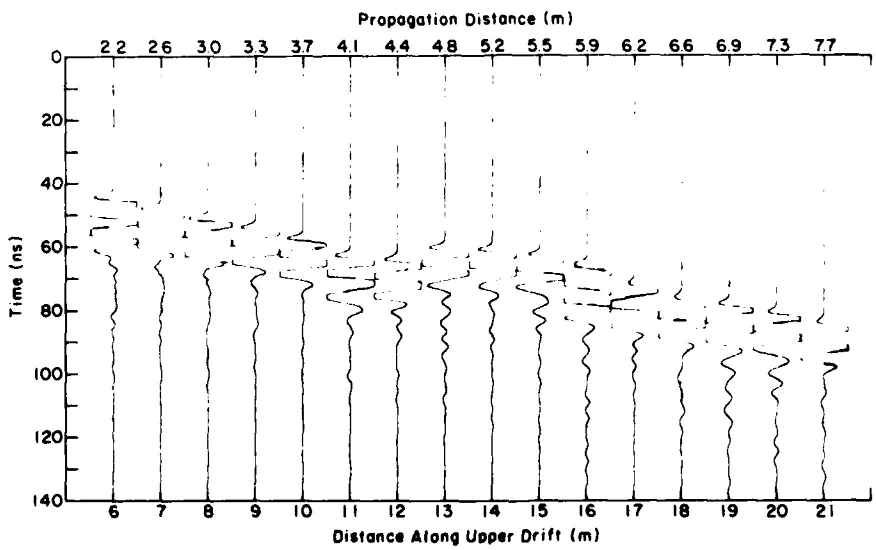


Figure 3. Pulses transmitted through the tunnel septum.

Transmissions to the surface

These experiments were conducted in April 1982 and 1983. In 1982 transmissions were attempted from the ground surface above the rear of the tunnel near the ventilation shaft (area 3 in Fig. 1) to a fixed receiver butted against the ceiling and moved down the drift from the shaft. In 1983 the transmitter was fixed on the very high ceiling at the front of the tunnel (area 2 in Fig. 1), and the receiver was moved transverse to the tunnel axis on the surface. Polarization was horizontal and transverse to the tunnel axis in both cases.

The 1983 transmissions are shown in Figure 4; these are sharp events with an easily identifiable leading edge. Only station 14 shows any significant waveform degradation. The pulse periods are consistently 10 ns, which gives an approximate spectral center frequency of 100 MHz. This consistency would ordinarily imply that no dispersion occurred, particularly because of the different propagation paths and path lengths. The maximum difference between path lengths was 2.2 m (between the vertical and the most offset paths). However, the decrease in center frequency from that of the tunnel septum spectrum reveals that dispersion did take place, although not as severely as at the rear of the tunnel. The septum waveforms of Figure 3 also show one to two more oscillations than the waveforms of Figure 4. This indicates bandwidth broadening and gives further evidence for dispersion. This dispersion probably occurred in the main body of the overburden due to absorptive effects and possibly from scattering.

Table 1 gives the apparent dielectric constants computed for each station above the tunnel. The calculations are "apparent" in that they assume refractionless, straight-line propagation. The values are largest for the shortest paths (where the receiver is directly above the transmitter) and smallest where the receiver is off axis. The difference in values is probably due to a temperature-controlled dielectric structure, where dielectric constants are lowest near the colder surfaces and highest in the warmer interior. When propagation is off axis in this type of structure, the resulting refraction makes the pulse take longer to pass through layers with lower dielectric constants, making the off-axis apparent values less than the on-axis value.

Near the ground surface at this time of year, temperatures may still be below $-2\,°C$ (Crory 1960). Since the tunnel is refrigerated in winter by circulating outside air, temperatures near the tunnel walls are also lower, having been measured at $-7\,°C$ between 1 and 2 m deep. Within the main body of the overburden, however, temperatures are probably no lower than $-2\,°C$. Therefore, relative dielectric values may have been no greater than about 7 within 2 m of both the transmitter

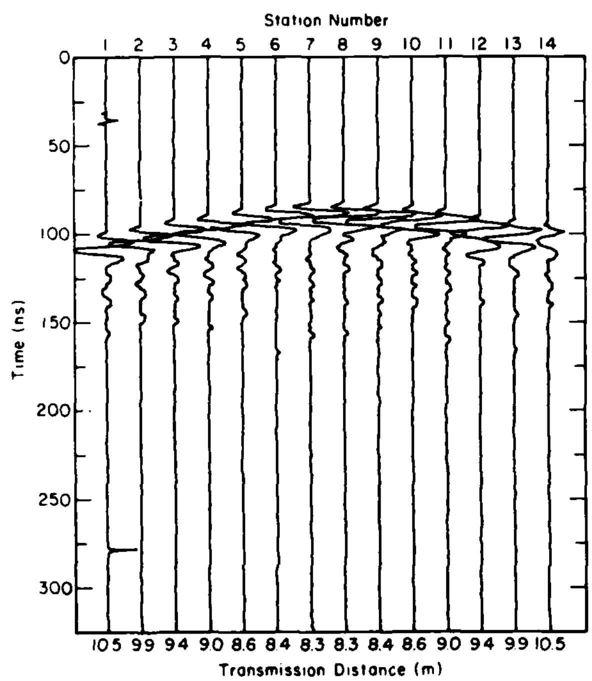


Figure 4. Pulses transmitted through the overburden above the permafrost tunnel (study area 2).

Table 1. Apparent dielectric constants for the tunnel overburden.

Station	*Straight-line propagation distance (m)*	*Apparent dielectric constant*
1	10.5	7.8
2	9.9	8.3
3	9.4	8.6
4	9.0	8.9
5	8.6	9.0
6	8.4	9.0
7	8.3	9.1
8	8.3	9.1
9	8.4	9.0
10	8.6	8.8
11	9.0	8.5
12	9.4	8.6
13	9.9	8.1
14	10.5	7.4

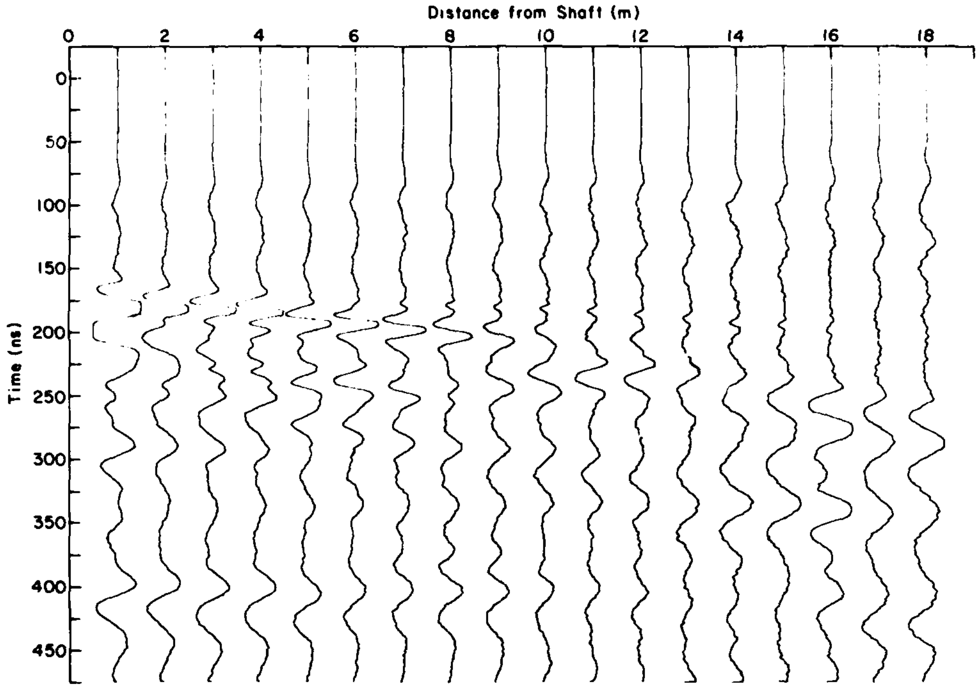


Figure 5. Transmissions from the ground surface to the tunnel ceiling at the rear of the tunnel (study area 3). The transmitter was above the 7-m mark.

(especially) and the receiver, and between 10 and 12 within the overburden for this ice-rich, organic silt (Delaney and Arcone 1982).

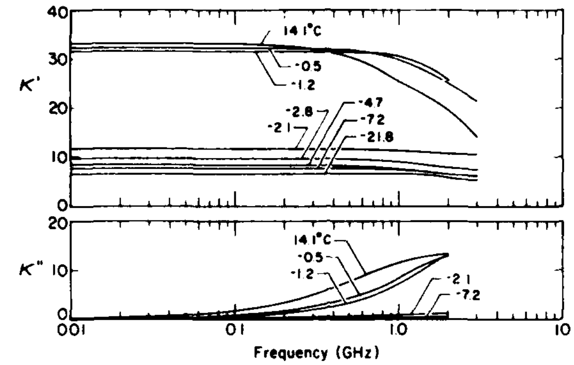
The transmissions at the rear of the tunnel (area 3 in Fig. 1) have been discussed previously (Arcone and Delaney 1984) and are presented in Figure 5 for comparison with the more recent data. The approximate 155-ns delay for the strongest arrival at the bottom of the shaft is approximately what would be predicted for the direct propagation path of 13.9 m through warm permafrost (about -2°C) for $\kappa' = 11$ (Delaney and Arcone 1982). This suggests that the transmissions were directly through the permafrost and that the decrease in time delay with distance from the shaft was due to refraction effects that might have been caused by dipping stratification in the overburden. The lack of a consistently identifiable leading edge on the pulses precluded the compilation of a meaningful table of dielectric values for all the transmissions.

Since the estimated direct-path maximum attenuation was about 72 dB, the direct signal should be observable, as it was. The degree of low-frequency shift (with a center frequency of approximately 50 kHz) is not predicted by conductive absorption effects (Arcone 1981) because of the relatively high resistivity (more than 400 Ω-m) that occurs between 0° and -2°C in organic Fairbanks silt (Arcone et al. 1979). It was, however, predicted by dipolar effects, which would occur within the main body of the overburden where dielectric constant values are highest. The higher frequencies also may have scattered, as may be evidenced by the many arrivals.

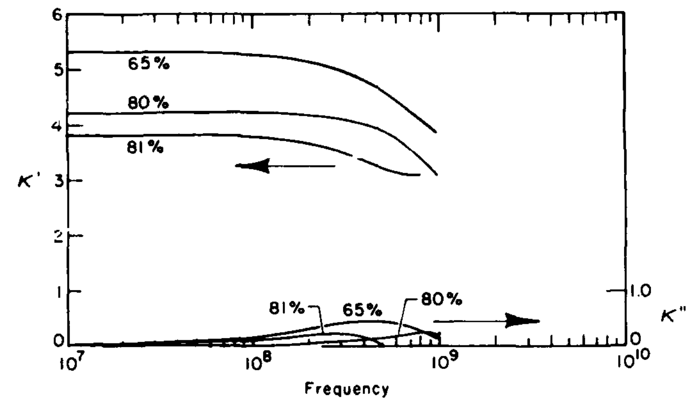
DISCUSSION

The two fundamental concerns in pulse transmission measurements are loss of amplitude and degradation of waveform. The important processes that determine these effects are absorption, scattering, and of course, loss in amplitude due to geometric spreading of the beam. The effects of absorption and spreading can be calculated. The effect of scattering is best determined by experiments, as it is difficult to theoretically account for the inhomogeneity of a naturally occurring material.

In these experiments I have observed pulse distortion but have not measured attenuation. The effective dielectric constants of the septum were between 3.8 and 7.1, and the transmitted center-



a. Prepared laboratory samples.



b. Field samples.

Figure 6. Complex relative dielectric permittivity of high-ice-content frozen silt. Percentages are volumetric water contents. Note the lower relaxation frequencies for the naturally occurring material. κ" is the imaginary part of the dielectric constant as discussed in Appendix A. (After Delaney and Arcone 1984.)

spectrum frequency was highest at 180 MHz. At the front of the tunnel, effective dielectric constants were between 7.4 and 9.1, with a transmitted frequency of 100 MHz. At the rear of the tunnel, the measured dielectric constant was about 11 at 50 MHz with serious distortion. In all cases the transmitting and receiving antennas were placed against frozen ground that was cold enough (i.e. with a low enough dielectric constant) to keep the natural resonant frequency of the antennas above 150 MHz. Therefore, this lowering of frequency is likely to have been caused by transmission through the main body of the permafrost.

Laboratory measurements of dielectric properties of frozen silt adapted from Delaney and Arcone (1982, 1984) show that such dielectric values are indicative of frozen silt no warmer than about −2°C (Fig. 6). These measurements also show that dielectric relaxation frequencies may range between 0.3 and 1.0 GHz in naturally occurring, high-ice-content frozen silt. Figure 7 is a graph of the dielectric constant as a function of volumetric water content for both prepared laboratory and extracted tunnel samples. The graph shows that above about 40% water content, the dielectric constant has a unique dependence on volumetric

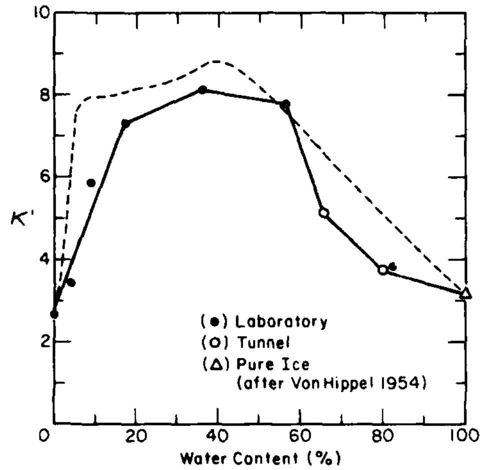


Figure 7. Dielectric constant as a function of volumetric water content for prepared laboratory and in-situ tunnel samples of frozen silt (solid line). The frequency is 500 MHz, and the temperature is −7°C. The dashed line is the theoretical model curve. (After Delaney and Arcone 1984.)

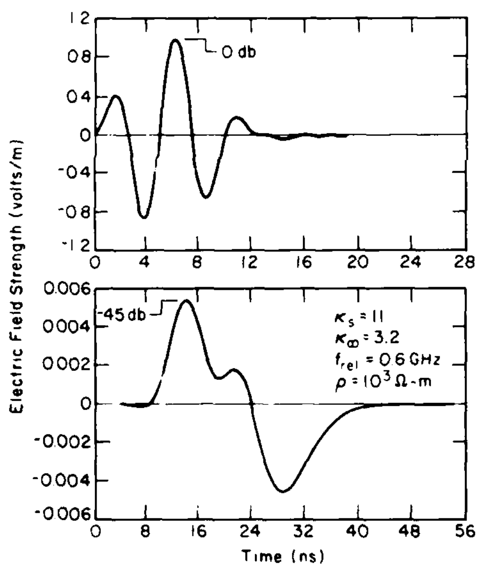


Figure 8. Distortion and attenuation of a model radar waveform after propagating through 13.9 m of a model frozen silt. The top waveform is the original pulse; the bottom is a distortion of the original pulse. The simulation is intended to model the data of Figure 5.

water content. These data imply that the average water content at the front of the tunnel throughout the overburden was between 40 and 60%, while within the septum it ranged between 60 and 80%.

Figure 8 shows a computer simulation of a model radar pulse propagating through material simulating the overburden at the rear of the tunnel. The modeling technique is discussed in Arcone (1981), and the material parameters are described in Appendix A. The simulation verifies that the frequency spectrum of the radar pulses can be severely decreased by this material. In this case the bulk of the distortion and attenuation is due to dipolar relaxation and not conductive absorption. The resulting waveform is similar to those of Figure 5, and the total attenuation (absorption and geometric spreading) for the propagation distance of 13.9 m would be 68 db, which is very close to that estimated for the rear of the permafrost tunnel.

A further consideration is the effect of scattering. Inclusions within the frozen silt ($\kappa' = 11$), such as ice lenses ($\kappa' = 3.2$), will cause scattering and therefore a loss of energy at wavelengths comparable to the dimension of the inclusions. If the inclusions are smaller than a typical in-situ wavelength (typically 60 cm or less), the scattering process will act like a low-pass filter and shift the pulse spectrum lower. Therefore, it is conceivable that small structures of clear ice could reshape the frequency spectrum.

CONCLUSIONS

Deep, one-way transmissions through ice-rich permafrost will be most successful where the ground temperature is about −4°C or less, or where there are large amounts of massive ice, such as tabular lenses. Calculation of the dielectric constant from the pulse travel times would then allow bulk values of ice content to be estimated from references such as Figure 7. It is possible that transmissions over distances of 30 m, which could be expected for some geotechnical investigations, could be successful even at marginal permafrost temperatures. However, at such high temperatures the true leading edge of a pulse may be lost in the noise level, making dielectric measurements and therefore estimates of ice content inaccurate.

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APPENDIX A: DEBYE-TYPE DIELECTRICS

Materials containing unfrozen water, whether free or bound to the material, exhibit frequency-dependent dielectric properties in the VHF through microwave-frequency range. This type of frequency dependence was first discussed by Debye (1929) and is described as a relaxation-type phenomenon. In a relaxation-type process the atomic or molecular dipoles (water molecules are permanent dipoles) fail to keep in phase with the impinging electromagnetic field within a critical frequency range, so they convert the electromagnetic energy into heat. The characteristic frequency at which this happens is known as the relaxation frequency. For liquid water at 20°C it is about 22 GHz, and at 0°C it is about 9 GHz. For water adsorbed on thawed soils it is generally between 1 and 9 GHz and may range as low as 100 MHz for frozen soils.

Mathematically the complex relative dielectric permittivity κ^* may be expressed as

$$\kappa^* = \kappa_\infty + \frac{\kappa_s - \kappa_\infty}{1 + if/f_{rel}} \qquad \text{(A1)}$$

where κ_s = low-frequency (or static) dielectric constant

κ_∞ = high-frequency (or electronic) dielectric constant

f = frequency of excitation

f_{rel} = relaxation frequency

$i = \sqrt{-1}$.

The quantities κ' (as discussed in the text) and κ'' are the real and imaginary parts of κ^*. The complex index of refraction $n^* = \sqrt{\kappa^*}$.

The quantities κ' and κ'' are as follows:

$$\kappa' = \kappa_\infty + \frac{\kappa_s - \kappa_\infty}{1 + (f/f_{rel})^2} \qquad \text{(A2)}$$

$$\kappa'' = \frac{\kappa_s - \kappa_\infty}{(1 + f/f_{rel})^2} \qquad \text{(A3)}$$

The resistivity of a material contributes to the value of κ'', so that the effective value of κ'' over all frequencies is

$$\kappa''_{eff} = \kappa'' + \frac{1}{2\pi f \varrho \epsilon_0}$$

where ϱ is the resistivity in Ω-m and ϵ_0 is 8.85×10^{-12} F/m.

Experimentally Delaney and Arcone (1984) found for wet silts generally colder than −2°C that over the entire frequency range of measurement, κ'' is about half or less of the value that is predicted by eq A3. This is probably due to the dispersional effects of absorbed water (the Debye analysis was based on a model of liquid water). This factor of one half has been included in the modeling of Figure 8.

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